Abstract—The evaluation of R&D projects in a high technology firm is very important. A lot of them quite often do not lead to new products as management did not take into consideration indexes such as probability of commercial success, technological success, strategic fit, etc which cannot be expressed in a quantitative form. An efficient and reliable approach for evaluating R&D projects capable of handling simultaneously the quantitative and qualitative criteria involved based on the theory of Fuzzy Logic is presented and a software model of the approach has been developed and tested in a real environment. It is a multiple criteria decision-making method where all projects are rated according to a number of quantitative and qualitative criteria capturing possibilities of technical and commercial success and the consistency of the projects with business strategy. We report on the criteria used for the evaluation of the projects and on the operation of the software model.

Keywords: Selecting R&D projects, qualitative criteria, fuzzy sets, portfolio management, new product development.

I. INTRODUCTION

High technology firms face an environment characterized by frequent innovation, high mortality rates, high priority on research and development, stiff competition in a race to the marketplace and partnerships with firms that may be potential competitors. The product development process in high technology environments relies on many of the same concepts used in more traditional environments, but it differentiates itself in a number of ways [1]. In addition it is necessary for them quite often to undertake many R&D in order to acquire the necessary technology and know how for developing their future New Products. Regarding their product range they continue to categorize their products and they classify them on a continuum ranging from incremental to radical innovations [3], but as it was stated before the number of products are quite high. The product life cycle is also very important, as it tends to shrink continuously, while the development times are very long. Of special interest is the technology life cycle, aiming at improving the underlying technology of a product and its price performance ratio. However, a number of technologies are under development, all-competing for the same range of products and none of them can be considered unless experimenting with them. Again the life cycle of the technologies is rather short and product managers should anticipate when new technologies might supersede existing technologies.

Adoption and diffusion of innovation are often concepts useful in managing both high and low technology products. One critical issue is the development of a technology map to guide their investments and resource allocation within the firm. In addition, it is quite often to form alliances and to partner with others in the new-product development process, allowing them to access other skills and resources. The development of a system to prioritize their projects and to assist the management of these projects is a critical management task [2,4,5], as:

- It is directly related to resource allocation within the firm and it provides an estimate on the budget that the company will allocate to the development projects.
- It is related to the corporate strategy. It may predict the products and the technologies, which will receive top priority and will be first introduced to the market. The new products that the company will introduce in the market will determine its profile. It has been estimated that 50 percent of firms’ sales today come from new products introduced within the last five years [2,10].
- It predicts the product mix that a company is developing. Every company, especially the high tech ones, should have a proper and feasible mix of projects under development, in terms of risk, income, short and long term aims, etc.
- Portfolio management can be a valuable decision support tool for the management, as it can evaluate the current projects and prioritize them, thus providing support for decision regarding, [2]
  - The projects which are the most promising and the additional resources necessary to bring a product to the market faster
  - The projects which are the least significant ones and which can be stopped and reallocate the resources to other projects, which are ranked higher.

However, the evaluation process is not an easy one and it is not static. There are multiple goals and strategic considerations, relations between the several projects and many decision makers with different background and knowledge. As a process it should take place periodically and the time period depends upon the type of the company and the process should include all projects within the department. As a problem is not a new one and it has been a subject of research for many years. It has been called “R&D project selection”, “R&D resource allocation”, “project prioritization” and “portfolio management”. The first methods proposed were of constrained
optimization under conditions of uncertainty; a multi-project, multi-stage decision model solved by mathematical programming techniques, such as linear, dynamic and integer programming. The objective was to develop a portfolio of new and existing projects to maximize some objective function (for example, the expected profits), subject to a set of resource constraints. In general the mathematical models were incomplete because they failed to include in their consideration all relative estimates for making an appropriate project evaluation [15], such like commercial and technical success and strategic fit and they required from the company to understand the way the constrained optimisation model works. In addition it could not ensure that the results obtained were strategically aligned, the model was not robust and it was very sensitive.

II. PROJECT SELECTION UNDER FUZZY ENVIRONMENT

The process of classifying and subsequently choosing R&D projects for developing new products is operating in an environment of uncertainty and ambiguity. Certain objective goals and criteria are often difficult to be measured with district values and for this reason they are not included in the evaluation process. However, the mathematical models that are most often used by the companies are based on distinct values for the parameters and they do not capture the uncertainty and ambiguity of the decision makers. In addition, the indexes that a company has for evaluating and selecting R&D projects and finally compose its portfolio with new products are complex and frequently inaccurate. They also fail in measuring qualitative objectives and criteria with distinct parameters, which are required by many of the evaluation methodologies. A good approach for evaluating R&D projects should have the possibility of conversing and evaluating simultaneously both the quantitative and the qualitative criteria. Even when all the information used for the evaluation of R&D projects is quantitative, the process of evaluation is from its own subjective. Many decision makers that participate in the evaluation process are likely to find that the analytical process of evaluation and selection is restrictive and for this at least in one stage of the process they use subjective methods.

The complex process of composing a portfolio with new products makes essential the utilisation of a methodology that will have the possibility of evaluating inaccurate information about the characteristics of the new products. The Fuzzy Logic theory employs approximate, rather than exact, mode of reasoning, and therefore incorporates imprecise, linguistic and subjective values. Fuzzy Logic theory is a convenient and flexible tool for dealing with linguistic descriptions and situations.

The criteria for the evaluation of R&D projects can be both quantitative, using numeric (crisp) variables and qualitative using linguistic variables, which are described as fuzzy sets.

The present work uses the Fuzzy Logic theory in the evaluation of R&D projects. The R&D projects are evaluated on many criteria where some of them are quantitative while the rest are qualitative. At that point the use of Fuzzy Logic gives the possibility of combining two different categories of criteria and finally gives one value that expresses the score of each project. The final selection of R&D projects is based on the total available budget for research and development in new products.

III. CRITERIA FOR THE EVALUATION OF R&D PROJECTS FOR NEW PRODUCTS

Next step in the development of the fuzzy model is the development and the adoption of suitable criteria in order to evaluate the projects. The criteria are given in a form of questions and each decision-maker should answer them. The model by itself is a scoring model. Scoring models have a big history as a process for evaluating projects and composing a portfolio [2]. However a lot of these scoring models failed to satisfy their goal. The reasons that led to this situation were the inadequate criteria that were used and the problems that happened at their utilization in the meetings of the administration.

The scoring model we present includes a list of 17 questions that belong in five main criteria. Each question or criterion has been carefully selected and formulated so that it will be a capable, reliable and essential criterion for evaluating each project. Similar criteria have been also used by big companies [2,10] and have been tested for their value and reliability after many years of application. These criteria were appreciated and evaluated for their value and their importance by an end user.

The five main criteria that included in the proposed model are:

- Reward (in the company)
- Strategic Force and Leverage
- Alignment with the Strategy of the Company
- Commercial Success
- Technical Success

As it was mentioned above, each criterion includes a range of questions (sub-criteria). Some of these sub-criteria are quantitative (the 1st criterion) while the rest are qualitative. At the quantitative sub-criteria the decision-maker gives his answer in distinct form, while in the qualitative in each question a list of pre-selected answers (multiple choice) are offered. This is also the most strong point of the proposed method, the combination of quantitative and qualitative data.

IV. MODELING THE PROBLEM WITH FUZZY LOGIC

The next step is the modeling of the problem using fuzzy logic. The foundations and the basic definitions about fuzzy sets are explained in the literature [6,7,8,9] and it will not be presented analytically here. Only the modeling of the problem will be presented. It is faced as a case of multi-criteria analysis of many R&D projects with multiple decision-makers and multiple objectives.
Because of the ambiguity that exists in the grading of R&D projects, all answers on the criteria and respectively at the sub-criteria are received as linguistic variables. The linguistic variables can better represent the knowledge, the experience and the subjective point of view of the decision-makers in more intuitive way and natural language format. Each linguistic variable can be expressed using fuzzy numbers and membership functions, which they have various forms. Trapezoidal-shaped membership functions are common, but unrealistic in their representation of uncertainty, because of the sharp transitions used [11]. For more gradual transitions, it is convenient to employ $s$ and $\pi$ functions. The definitions of these functions [12] are as follows:

$$S(x; \alpha, \beta, \gamma) = \begin{cases} 0 & x \leq \alpha \\ 2 \left[ (x-\alpha)/(\gamma-\alpha) \right]^2 & \alpha < x \leq \beta \\ 1-2 \left[ (x-\gamma)/(\gamma-\alpha) \right]^2 & \beta < x \leq \gamma \\ 1 & \gamma < x \end{cases}$$

$$\pi(x; \alpha, \beta, \gamma) = S(x; \gamma-\beta, \gamma/2, \gamma)$$

where $x$ is any object in the universe of discourse, $\alpha, \beta, \gamma$ are adjustable parameters.

As it was mentioned above for each qualitative sub-criterion there are five or four pre-selected answers that are given in verbal form and they describe the status of the R&D project. Each of these verbal answers is a linguistic variable that is expressed with a fuzzy number and exactly with the membership function of the fuzzy number which shape is $s$ or $\pi$.

The membership functions are shown in fig.1. The fuzzy numbers that corresponding to the answers for the case of the five pre-selected answers are approximately 0, 0.2, 0.5, 0.8, 1.0 and for the case of the four pre-selected answers are approximately 0.1, 0.4, 0.7, 1.0.

As it was mentioned above for each qualitative sub-criterion there are five or four pre-selected answers that are given in verbal form and they describe the status of the R&D project. Each of these verbal answers is a linguistic variable that is expressed with a fuzzy number and exactly with the membership function of the fuzzy number which shape is $s$ or $\pi$.

The membership functions are shown in fig.1. The fuzzy numbers that corresponding to the answers for the case of the five pre-selected answers are approximately 0, 0.2, 0.5, 0.8, 1.0 and for the case of the four pre-selected answers are approximately 0.1, 0.4, 0.7, 1.0.

The first answer of each sub-criterion is expressed with the first fuzzy number and respectively the others. The fuzzy numbers express the contribution of each project in the particular sub-criterion and answers from the first to the fifth or the forth is a better condition for the project.

Concurrency with the answer that the decision-maker gives, he has also the opportunity to add a weight in each one of the main criteria. This parameter is very important because it gives a profile in the portfolio that will be created. The weights are given in district form and their sum should be one.

A. Mathematical Modeling

We consider that we have a problem with $K$ decision-makers who will evaluate $m$ R&D projects in the $n=17$ sub-criteria that were reported. The contribution of each project from each decision-maker in each sub-criterion is $x_{ij}$ where $i$ is the examined project and $j$ is the sub-criterion in which it is evaluated, while $K$ is the decision-maker. The results of this is the total scoring of each program in the particular criterion, which is

$$\text{score} = \frac{1}{K} \sum_{j=1}^{K} x_{ij} = \frac{1}{K} \sum_{j=1}^{K} (x_{ij} + x_{ij} + \ldots + x_{ij})$$

where $x_{ij}$ is the fuzzy score of the project $A_i$ based on the criterion $C_j$ and

The weight that the decision-maker gives in each one of the five criteria is $w_l$ where $l$ is the criterion ($l=1$ to 5) and therefore the total weight of each criterion is

$$w_l = \frac{1}{K} \left[ w_{l1}^1 + w_{l2}^2 + \ldots + w_{lK}^K \right]$$

As it mentioned above the sub-criteria belong in five categories of criteria, so the weight of each sub-criterion is $w_j = \frac{w_{lj}}{s_j}$ where $j=1,\ldots,n$ and $w_{lj}$ is the weight of the criterion in which the sub-criterion belongs and $s_j$ is the number of sub-criteria that the criterion has.

The result of the evaluation of $m$ R&D projects $A_1, A_2, \ldots, A_m$ in 17 sub-criteria $C_1, C_2, \ldots, C_n$ is the table that gives the multiple-criteria decision from all the decision-makers:

$$D = \begin{bmatrix} x_{11} & \Lambda & \Lambda & \ldots & x_{1n} \\ \vdots & \Lambda & \Lambda & \ldots & \vdots \\ x_{m1} & \Lambda & \Lambda & \Lambda & x_{mn} \end{bmatrix}$$

$$w = [w_1, \ w_2, \ \Lambda, \ w_n]$$

where $x_{ij}, \forall i,j$ is the fuzzy score of the project $A_i$ and $C_j$ based on the criterion $C_j$ and
\( w_j \ (j = 1, \ldots, n) \) is the weight. The fuzzy records of the projects in each sub-criterion are linguistic variables and they can be represented as fuzzy numbers of \( s \) and \( \pi \) form. The parameters for these functions are three, so the relation fixes the fuzzy number is 

\[ x_j = (a_{ij}, b_{ij}, c_{ij}) \, . \]

In order to ensure compatibility between evaluation of objective criteria and linguistic ratings of subjective criteria, the linear transformation is used to transform the various criteria into a compatible scale. Therefore, we can obtain the normalized fuzzy decision matrix denoted by \( \tilde{R} \) as

\[ \tilde{R} = \left[ \begin{array}{c} \tilde{r}_{ij} \end{array} \right]_{mn} \]

\[ \tilde{r}_{ij} = \frac{a_{ij}}{a_{ij} + b_{ij} + c_{ij}}, \quad a_{ij} = \min_{i} a_{ij} \]

\[ \tilde{r}_{ij} = \frac{b_{ij}}{b_{ij} + c_{ij}}, \quad b_{ij} = \min_{i} b_{ij} \]

\[ \tilde{r}_{ij} = \frac{c_{ij}}{c_{ij}}, \quad c_{ij} = \min_{i} c_{ij} \]

where \( B \) is the set of quantitative criteria that should be minimized and \( C \) the quantitative criterion that should be increased. As we mentioned above these criteria have district values so \( a_{ij} = b_{ij} = c_{ij} \).

With this process of normalization the scoring and more specifically the attribution of each program on each sub-criterion takes in the price interval \([0,1]\).

### B. Calculating the fuzzy weighted average (FWA)

In order to aggregate projects’ fuzzy achievements into a single fuzzy set, there is a need to use a fuzzy aggregate operation. For this model we used the well-known weighted average operator which has been extended so that it collaborates with fuzzy variables. The operator is the fuzzy weighted average (FWA). According to Schumucker [13] this is:

\[ \tilde{X_i} = \frac{\sum_{j=1}^{n} w_j \tilde{x}_{ij}}{\sum_{j=1}^{n} w_j} = \sum_{j=1}^{n} w_j \tilde{x}_{ij} \]

\( \forall i (i = 1, \ldots, m) \),

where \( m \) is the number of potential R&D projects, \( n \) is the number of the sub-criteria, \( \tilde{x}_{ij} \) is the fuzzy value of project \( j \) according to the sub-criterion \( i \) \((i = 1, \ldots, m \) \& \( j = 1, \ldots, n) \) and \( \bar{I} \) is the relative district weight of the sub-criterion either for a qualitative or a quantitative criterion. Using normalized weights \( \sum w_j = 1 \).

\( \tilde{x}_{ij} \) is a representation of the scoring of the project \( i \) \((i = 1, \ldots, m) \). Since \( w_{ij} \) is a crisp number while \( \tilde{x}_{ij} \) is a fuzzy number, their multiplication is a fuzzy operator giving a fuzzy set, \( \tilde{w}_j \tilde{x}_{ij} \). The expression \( \sum \tilde{w}_j \tilde{x}_{ij} \) is the fuzzy weighed average of projects’ achievements, which is also a fuzzy set.

There are two methods for the calculation of fuzzy weighed average (FWA), the direct method extends the ordinary algebraic operations to fuzzy algebraic operations and the indirect method. This method based on the \( \alpha - cut \) representations of fuzzy sets and performs the extended algebraic operations by manipulating the fuzzy intervals at each \( \alpha - cut \).

At the present work the indirect method was preferred [11] and the steps that are followed are:

i. The interval of prices \([0,1]\) of the membership functions discretized into finite numbers of values (\( \alpha \) levels).

ii. For selected \( \alpha \) levels, \( \alpha - cut \) intervals are obtained for each linguistic variable and each rating scale.

iii. For each crisp variable, all the a-cuts are identical and defined as a point and not as interval, whose value is a normalized value in the interval \([0,1]\).

iv. For each \( \alpha \) level, the following interval is calculated:

\[ [a_{\alpha,i}, b_{\alpha,i}] = \frac{\sum_{j=1}^{n} w_j \tilde{x}_{ij}}{\sum_{j=1}^{n} w_j}, \quad \text{for } i = 1,2,\ldots,m \text{ and } \alpha = 0.0,\ldots,1.0. \]

The \( \alpha \)-values and the resulting intervals approximately define the \( \alpha - cut \) representation of the FWA. At this problem an FWA of objectives was calculated for each program \( i \).

### C. Defuzzification of FWA

Since the FWA is a fuzzy set, it is impossible to compare projects and rank them. In order to do this, a transformation of the fuzzy values into crisp values is required. We use a defuzzification technique, such as the improvement urgency index (IUI) [11]. This index
is calculated by taking a weighed average of the midpoint of each interval. The equation for this transformation of project $i$ FWA to crisp IUI \[14\] is:

$$
IUI_i = \sum_{a_i=0.0}^{1.0} \alpha \left( a_{a.i} + b_{a.i} \right)/2
\sum_{a_i=0.0}^{1.0} \alpha
$$

for $i = 1,2,...,m$

where $a_{a.i}$ and $b_{a.i}$ are the end points of the interval at the $\alpha$-level of the membership function of the calculated FWA.

V. RANKING THE PROJECTS

After the calculation of the score of each project, the next step is the classification of the projects. A “good” project is one, which has a high ratio between its achievement and its resource requirements. With this method a project with low score and low cost of investment has a good score. It does not also penalize projects with high cost because these projects most of times have a bigger score so they have a good ratio score/investment cost. This ratio finds the value of project per unit of its development cost.

The list, with the R&D projects that will compose the portfolio of new products, stops at the point that the total cost for developing these products is equal to the budget that the company spends for new products.

VI. CONCLUSIONS AND DISCUSSIONS

The main characteristic and simultaneously the main advantage of the fuzzy model, is the capability that it has to evaluate R&D projects according to a range of objectives that capture many characteristics of the new product they are aiming at. These parameters are the Commercial Success, the Technical Success and the Strategic Fit.

An additional characteristic of the developed model is the possibility of leading the three objectives that a company has at the composition of its portfolio. The 1st criterion achieves the maximization of the value, while the 2nd and the 3rd link the portfolio with the company’s strategy. Finally the 4th and 5th criteria managing the risk that the new products have.

The fuzzy logic theory gives to the model the essential robustness. The ambiguity that exists in the estimate of the status of a project is combined very well with fuzzy logic that adopts the present model. The comparative advantage of this model is that in case where the decision-maker made a wrong evaluation, this does not change dramatically the optimal portfolio.

At the same time the particular model has the possibility of dealing and using simultaneously both verbal and crisp variables. This is a privilege characteristic of the fuzzy logic which has the possibility, with the use of the operators that was reported above, to exploit the two kinds of data without any limitation.

Concluding, the fuzzy model gives the possibility to a team of decision-makers to evaluate and rank a group of new products. Each decision-maker gives his own weights at the criteria and thus to give his personal estimate for the balance that will have the portfolio. The particular methodology can help decision-makers to take the suitable decisions under an environment of ambiguity and continuous evaluation.

References

[14]. Chen-Tung Chen, A fuzzy approach to select the location of the distribution center, Fuzzy
Sets and Systems, Volume 118, Issue 1 16
February 2001Pages 65-73.